BNL-113200-2016-IR

C-A/AP/568
November 2016

A Summary of an Inter-Directorate C-AD/NSTD "Accelerator Driven Subcritical Reactor" Collaboration

F. Méot, A. Aronson, M. Bai, D. Brown, N. Brown, M. Haj Tahar, M. Herman, A. Hershcovitch, B. Horak, H. Ludewig, S. Peggs, P. Pile, T. Roser, N. Simos, M. Todosow, D. Trbojevic, N. Tsoupas, W.T. Weng

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

Notice: This document has been authorized by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy. The United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this document, or allow others to do so, for United States Government purposes.

A SUMMARY OF AN INTER-DIRECTORATE C-AD / NSTD "ACCELERATOR DRIVEN SUBCRITICAL REACTOR" COLLABORATION

F. Me´ot, A. Aronson, M. Bai, D. Brown, N. Brown, M. Haj Tahar, M. Herman, A. Hershcovitch,
B. Horak, H. Ludewig, S. Peggs, P. Pile, T. Roser, N. Simos, M. Todosow,
D. Trbojevic, N. Tsoupas, W.T. Weng

C-AD and NSTD Departments
BNL, Upton, NY 11973
November 4, 2016

Abstract

A summary of the activities and of the scientific production of the "NSTD/C-AD ADS-Reactor Think-Tank" collaboration, over the period May 2013 - May 2015.

Tech. Note NSTD and C-A/AP/568
Brookhaven National Laboratory

Contents

1 INTRODUCTION **3**

2 GOALS **3**

3 TALLY **5**
3.1 ADS-Reactor Collaboration Meetings . . . 5
3.2 A Talk Series . . . 5
3.3 Written Contributions . . . 5
3.4 Workshops at BNL . . . 7
3.5 Collaborations . . . 7
3.6 Student Programs . . . 7
3.7 Publications . . . 7

4 WHAT NEXT ? **7**

APPENDIX **9**

A Answer to ARPA-E 2013 call **9**

B Answer to DOE HEP “Request for Information” **13**

C FY15 LDRD, goals : A summary for NSTD and C-AD Department Chairs **18**

1 INTRODUCTION

This report is primarily a (selected) inventory of the scientific material produced by the "NSTD/C-AD ADS-Reactor" collaboration, and expressedly provides links to that material, including seminar slides, ARPA-E and other LDRD documents, etc.

It is also intended as a brief narrative of that short - yet rich of outcomes - event, that occurred at BNL during the past three years.

Some documents produced by the collaboration, which can be seen as landmark material, are included in appendix for reference, and for easier consulting.

A joint meeting has been held over the period May 2013 - May 2015, an inter-Directorate collaboration between BNL C-AD and NSTD Departments.

The 1-hour meeting periodicity was 2-week, more frequent at times for instance in bid preparation periods, less frequent during RHIC runs, eventually reaching a 40+ grand total over 25 months of activities. Location alternated between NSTD and C-AD Departments, usually on Thursday, 11am-12pm.

The collaboration developed and maintains a web site, "Accelerator Driven Subcritical Reactor" [1], where all the material produced over these 25 months of activities has been archived and can be consulted - from BNL IT network. It includes the slides of all presentations done during the meetings, meeting minutes, links to a host of documents and to various web sites relevant to ADS-R R&D (the latter include a link to a C-AD meeting series, run in parallel, dedicated to high power fixed field ring design studies, not addressed here).

Participation in these meetings was on a volunteering basis, the number of people who joined, at one moment or another, amounts to about 40, with generally 10∼15 attendees in the meetings (see the meeting minutes).

The meeting series was foreseen as a discussion forum, with active participation from C-AD and from NSTD, for progressing together in the learning, understanding, of the ADS-Reactor systems and their technologies, their challenges, issues, their societal and economical aspects. Such discussion forum was expected to foster good ideas, to be the place where proposals for such type of R&D funding requests as LDRDs and other SBIRs could be discussed and elaborated, and why not won, a location for fostering student and other PhD activities. The location, BNL, was deemed the right place for this forum, with the expertise at the NSTD and C-AD Departments, including the possibility of using RHIC injector complex for experimental work regarding high power beams, targetry, neutronics.

2 GOALS

This initiative of a meeting series on the theme of "accelerator driven subcritical reactors" resulted from a desire, shared by many people at C-AD and NSTD, to (i) progress in the knowledge and the understanding of the underlying physics, technologies, ambitions and other great questions, regarding nuclear energy and the particular technology of spallation based subcritical reactors, Thorium cycle, molten salt reactors, targetry, methods for high power beams, etc., and to (ii) get support for some practical realization (design study and other experimental work), likewise to foster that activity at BNL. All considered it of high interest to gather and involve in these thinking, people from the four disciplines : reactors, neutronics, high power proton accelerators, high power targetry. An inter-Directorate C-AD - NSTD collaboration was considered the right method to profit from the wide experience of many experts in both domains of reactors and accelerators, in enhancing and spreading knowledge.

This meeting series was also seen as an opportunity to address the interfaces between specialties, acquiring knowledge and competences at the frontier between beam, target, reactor core, nuclear data aspects in the ADS-Reactor method. With no imperatives of time limits, neither for the meeting duration (usually a reasonable 1 hour, however) nor for the extent of the collaboration (within and beyond BNL), it was deemed a great opportunity to be allowed time to think and debate together on these societal, economical and technological questions, an opportunity to dig into various "hot" actual topics relevant with these questions. To start with, a guideline - non exhaustive - list of possible topics to be addressed was proposed [1, May 16, 2013] (in alphabetical order) :

Accelerator technologies : RF, SCRF, magnet, design/prototyping ; Accelerator methods : cyclotron and FFAG, linacs, high power ; ADS and fast reactors in advanced nuclear fuel cycles ; BLAIRR ; Collaborations with other US labs ; Computer code developments ; Design and R/D challenges : accelerator, targetry, neutronic coupling ; Design study / possible prospects ; Efficiency: from wall plug to neutron production ; Energy production, transmutation ; Experimental programs at BNL / possibilities ; Fuels, U/Th, merits and disadvantages, liquid/solid, with/without ADS, fuel cycle ; Funding (finding) for prototyping, travel, hiring students, inviting experts, etc. : LDRDs, DOE and other calls ... ; Interface : k physics, k range ; Lectures, as part of the meeting series : reactors, neutronics, accelerators, ADS-R systems ; Neutronics, fuels : past experiments and future possibilities at the AGS ; Project sub-group : design study towards a small, molten salt, research ADS-Reactor ; Reliability ; Safety, non-proliferation ... ; Technico-economical aspects, cost comparisons between accelerator methods ; Thorium energy future ; Window, windowless methods ; Workshops and conferences to come, participation/reporting/organizing.

As will be seen in the next sections, it comes out that over its ∼2-year period of activities, the ADS-Reactor collaboration did address most of these topics, through 30∼45 minute presentations, discussions, design study proposals, collaboration and participation in workshops, publications, answers to DOE calls, etc.

Part of these achievements found themselves summarized in preparation to LDRD calls at BNL, under the form of a "Summary for NSTD and C-AD Department Chairs", a document aimed at establishing a frame for future joint C-AD/NSTD LDRD proposals, which can be considered a milestone in the collaboration and for this reason has been reproduced in appendix C.

The most meaningful of these outcomes are discussed below.

C-AD - NSTD
Inter-Directorate Collaboration
"Accelerator Driven Subcritical Reactors"

Send comments to M. Haj Tahar, x5573. **Last updated: 08/25/2016 10:23:18**

Useful links, documents

High Power Accelerator R&D for ADS-R

Meetings

meeting sessions	meeting minutes	meeting presentations	documentation
May 16, 2013	May 16, 2013	An "accelerator driven subcritical reactor" think-tank (F.Meot)	DOE white paper ; Thorium Energy Futures ; PASI Workshop ; List of papers on Innovative nuclear systems (ADS)
May 30, 2013	May 30, 2013	Energy-Amplifier (H.Ludewig and M.Todosow)	ADS paper Germany ; ADS_FFAG_White_paper ; IAEA_Thorium fuel cycles
June 13, 2013	June 13, 2013	Uniform Beams (N.Tsoupas)	Principles of the non-linear tuning of beam expanders; Non-linear tuning and halo transport in beam expanders
June 27, 2013	June 27, 2013	Introduction (FM) ; Fuel cycle evaluation and screening : overview of accelerator driven systems (N.R.Brown)	Thorium fuel cycle - Potential benefits and challenges
July 11, 2013	July 11 2013	Overview of PASI-II (W.T. Weng)	
July 23, 2013	July 23 2013	NPP Strategic Planning Meeting, BNL (FM)	
August 8, 2013	August 8, 2013	Introduction , Talk schedule (FM); Nuclear Data (D. Brown)	
Sept. 12, 2013	Sept. 12, 2013	Introduction , Talk schedule (FM); High power from linacs. ESS (S. Peggs)	
Sept. 26, 2013	Sept. 26, 2013	Introduction (Phil Pile); nTOF at AGS (Ph. Pile)	
Oct. 10, 2013	Oct. 10, 2013	Introduction (FM); Compact neutron source (Ady Hershcovitch)	Compact, energy efficient neutron source [...], C-A/AP/364 Note (Dec. 2009)
Oct 24, 2013	Oct. 24 2013	Introduction (FM) ; About the CSEWG meeting (M. Herman) ; "Transformative Hadron Beamlines" workshop (S. Peggs)	
Nov 07, 2013	Nov. 07, 2013	Introduction (FM) ; Return from ThEC'13 (F. Meot) ; Analysis on an Accelerator Diven System with Natural Uranium Fuel (N. Brown)	"Transformative Hadron Beamlines" workshop, update
Nov 14, 2013	Nov. 14, 2013	Return from ThEC'13 (cont'd) (F. Meot)	
Dec 05, 2013	Dec. 05, 2013	Introduction (FM) ; ADS-Reactor R/D Views (Mats Lindroos, ESS)	
Dec 13, 2013	Dec. 13, 2013	Introduction(F.Meot) ; ADS-R R&D and Strategic Plans (T. Roser) ; Accelerator Driven Systems: Utility Functions, Pasteur's Quadrant, and iPhones (B.Horak)	
Jan 9, 2014	Jan. 9, 2014	LDRD plans (F.Meot)	A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology ; DOE's Nuclear Energy Programs
Jan 23, 2014	Jan. 23, 2014	ADS Experiments at Kyoto University Critical Assembly (KUCA) (C. Pyeon)	Reaction Rate Analyses for an ADS with 14 MeV neutrons in KUCA
Feb 6, 2014	Feb. 6, 2014	Introduction (F. Meot) ; Plasma Window for Intense Beams Enabling Technology for Windowless ADS Targets (A. Hershcovitch) ; Talk schedule ; Joint C-AD/NSTD initiative for a LDRD thrust area in FY15	
Feb 13, 2014	Feb. 13, 2014	High Power Cyclotrons: Rationale and Possibilities (J. Alonso)	
Feb 20, 2014	Feb. 20, 2014	Introduction (F. Meot) ; Plasma Window for Intense Beams: Technology for Windowless ADS Targets (A. Hershcovitch) ; Vacuum-window Beam-target Beam-halo studies (N. Tsoupas) ; Target Design and Issues (M.Haj Tahar) ; High Power Ring Methods (F. Meot) ;	Blanket design studies of an LBE Accelerator Transmutation of Waste System
March 6, 2014	Mar. 6, 2014	Introduction (F. Meot) ; LDRD thoughts (B. Horak) ; NNDC LDRD ideas (D. Brown) ; Target Challenges in MW-level Accelerators for ADS (N. Simos) ;	Accelerator Driven Systems LDRD Area (joint between NSTD & C-AD)
March 13, 2014	Mar. 13, 2014	Possibilities of n-TOF Beam Line at BNL Hadron Complex (M. Bai)	
April 4, 2014	Apr. 4, 2014	Introduction (F. Meot) ; Thoughts on LDRD on Acceleator Driven Systems (N. Brown, M. Todosow) ; Nuclear Data Part of an S-LDRD (D. Brown) ; Joint CAD-NSTD LDRD proposal-High power beam R&D- (F. Meot) ;	
April 17, 2014	Apr. 17, 2014	Introduction (F. Meot) ; FFAG R&D at KURRI ADS Facility (Y. Ishi) ;	
May 1, 2014	May 1, 2014	Introduction (FM) ; ADS-LDRD_pptx ; ADS-LDRD_pdf (F. Meot, N. Brown, D. Brown) ;	Answer to DOE HEP "Request for Information" (Meot, Brown, Todosow)
May 15, 2014	May 15, 2014	Introduction (FM) ; Info: ARPA-E (B. Horak) ; High Power from Fixed-Field Rings in the ADS-Reactor Application (F. Meot) ;	
June 12, 2014	June 12, 2014	Introduction (FM) ; Accelerator Design & Modeling for the Decay-at-Rest Neutrino Experiments DAEdALUS & IsoDAR (D. Winklehner) ;	
July 3, 2014	July 3, 2014	Introduction (F. Meot) ; Discussion : joint NSTD/CAD proposal: "high power from fixed-field rings"	
July 10, 2014	July 10, 2014	Introduction (FM) ; ARPA-E Discussion : R&D contents of a possible joint NSTD/CAD proposal: "high power from fixed-field rings"	Proposed new program in Stewardship of Accelerator Technologies for Energy and Environmental Applications ; Answer to ARPA-E funding opportunity.
July 21-23, 2014		Transformative Hadron Beamlines Workshop, BNL	Summary slides, ADSR/Spallation target session
Jul 23, 2014		ACCELERATOR PHYSICS SEMINAR : "Presentation of MYRRHA Project and Its Role in the European P&T Strategy for High Level Waste Management" (Ait H. Abderrahim / SCK-CEN)	Abstract
September 22-26, 2014		FFAG'14 Workshop, BNL	Summary slides
Dec 3, 2014		Chinese Academy of Sciences, visit at BNL	Current Status of CADS (Zhan et al.) ; ADS Progress in China (Yang) ; BNL C-AD/NSTD ADS-R "think-tank" (F. Meot)
Dec 4, 2014	Dec. 4, 2014	Introduction (F. Meot) ; ANS14 feedback (M. Haj Tahar) ;	ANS14 meeting webpage
Dec 11, 2014	Dec. 11, 2014	CAS visit at BNL. ADS effort at BNL (F. Meot) ;	
Jan 22, 2015	Jan. 22, 2015	Introduction (FM) ; Accelerator Transmutation of Waste in the DOE-NE Evaluation and Screening (N. Brown) ;	
Feb 12, 2015	Feb. 12, 2015	Talk schedule (FM) ; Green Accelerators, plug-to-beam (S. Peggs) ;	
Mar 5, 2015	Mar. 5, 2015	Feedbacks from Dr. Hamid Ait Abderrahim, head of the MYRRHA project (M. Haj Tahar and N. Khatcheressian) ;	
Mar 26, 2015	Mar. 26, 2015	Introduction (FM) ; Inverse kinematics, neutron induced cross-sections (D. Brown) ;	
Apr 16, 2015	Apr. 16, 2015	Introduction (FM) ; Induction acceleration device for High Current Beams (N. Tsoupas) ;	
Apr 30, 2015	Apr. 30, 2015	Introduction (FM) ; The nuclear reaction model code EMPIRE (M. Herman) ;	
May 21, 2015	May 21, 2015	Introduction (FM) ; A review of FFAG methods (F. Meot) ;	FY16 joint LDRD proposal.

3 TALLY

3.1 ADS-Reactor Collaboration Meetings

A table of most of the meetings held by, or in the framework of, the ADS-Reactor collaboration is given in page 4, a copy of www.cadops.bnl.gov/AP/ADS_Reactor/, collaboration web site front page. Note that some specific meetings, for instance in preparation of DOE-HEP, ARPA-E and other LDRD calls - see section 3.3 below - do not appear in that list. Links in that front page of the ADS-R collaboration web site point to the meeting minutes (2nd column), to presentations (3rd column), and to dedicated documentation (4th column).

3.2 A Talk Series

Thirty five of the 40+ ADS-R think-tank meetings (page 4) included a 30∼45 minute presentation, followed by a discussion, the list is given below. Six (blue color) were formally invited seminars (KURRI ones on video/remote), the others were given by NSTD or C-AD contributors. All slides are available via *ad hoc* links in the collaboration website [1].

• **Energy-Amplifier**	H.Ludewig and M.Todosow / NSTD
• **Uniform Beams**	N.Tsoupas / C-AD
• **Fuel cycle evaluation and screening : overview of accelerator driven systems**	N.R.Brown / NSTD
• **Overview of PASI-II**	W.T. Weng / C-AD
• **Nuclear Data**	D. Brown / NSTD
• **High power from linacs. ESS**	S. Peggs / C-AD
• **nTOF at AGS**	Ph. Pile / C-AD
• **Compact neutron source**	Ady Hershcovitch / C-AD)
• **About the CSEWG meeting**	M. Herman / NSTD
• **Return from ThEC'13**	F. Méot / C-AD
• **Analysis on an Accelerator Diven System with Natural Uranium Fuel**	N. Brown / NSTD
• **ADS-Reactor R&D Views**	M. Lindroos / ESS
• **ADS-R R&D and Strategic Plans**	T. Roser / C-AD)
• **Accelerator Driven Systems: Utility Functions, Pasteur's Quadrant, and iPhones**	B.Horak / NSTD
• **LDRD plans**	F. Méot / C-AD
• **ADS Experiments at Kyoto University Critical Assembly (KUCA)**	C. Pyeon / KURRI-KUCA
• **Plasma Window for Intense Beams : Technology for Windowless ADS Targets**	A. Hershcovitch / C-AD
• **High Power Cyclotrons: Rationale and Possibilities**	J. Alonso / MIT
• **Target Design and issues**	M.Haj Tahar / C-AD
• **High Power Ring Methods**	F. Méot / C-AD
• **NNDC LDRD Ideas**	D. Brown / NSTD
• **Target Challenges in MW-level Accelerators for ADS**	N. Simos / NSTD
• **Possibilities of n-TOF Beam Line at BNL Hadron Complex**	M. Bai / C-AD
• **An LDRD related slide series :**	
Thoughts on LDRD on Accelerator Driven Systems	N. Brown, M. Todosow / NSTD
Nuclear Data Part of an S-LDRD	D. Brown / NSTD
Joint CAD-NSTD LDRD proposal-High power beam R&D	F. Méot / C-AD
• **FFAG R&D at KURRI ADS Facility**	Y. Ishi / KURRI
• **High Power from Fixed-Field Rings in the ADS-Reactor Application**	F. Méot / C-AD
• **Accelerator Design & Modeling for DAEdALUS & IsoDAR Neutrino Experiments**	D. Winklehner / MIT & PSI
• **AP Seminar: Presentation of MYRRHA Project and Its Role in the European P&T Strategy for High Level Waste Management**	Aït Hamid Abderrahim / SCK-CEN
• **Return from ANS14 Winter Meeting and Nuclear Technology Expo**	M. Haj Tahar / C-AD
• **Accelerator Transmutation of Waste in the DOE-NE Evaluation and Screening**	N. Brown / NSTD
• **Green Accelerators, plug-to-beam**	S. Peggs / C-AD and
• **The MYRRHA project**	M. Haj Tahar, N. Khatcheressian / MYRRHA
• **Inverse kinematics, neutron induced cross-sections**	D. Brown / NSTD
• **Induction acceleration device for High Current Beams**	N. Tsoupas / C-AD
• **The nuclear reaction model code EMPIRE**	M. Herman / NSTD
• **A review of FFAG methods**	F. Méot / C-AD

3.3 Written Contributions

A substantial volume of written documents have been produced during this collaboration, most of them available via the links found in [1]. Part of these concerned contributions to specific meetings, namely, to mention the most significant :

- NPP Strategic Planning Meeting at BNL
- ARPA-E funding opportunity
- DOE Accelerator Stewardship program and RFI
- CAS visit
- FY15 LDRD
- FY16 LDRD

These contributions are viewed as landmark material from the ADS-R collaboration, they are commented further in the following subsections.

NPP Strategic Planning Meeting

A BNL meeting. "NPP Strategic Planning Meeting", took place on July 23, 2013. The objectives of the initiative are to determine areas where BNL could possibly help in developing on-going efforts, and how.

The ADS-R think-tank contribution is available at [1, July 23, 2013 : "NPP Strategic Planning Meeting"].

ARPA-E funding opportunity

In September 2013, ARPA-Energy issued a funding opportunity announcement [2] :

"DE-FOA-0001002: OPEN INNOVATIVE DEVELOPMENT IN ENERGY-RELATED APPLIED SCIENCE (OPEN IDEAS)",

to which the ADS-R think-tank decided to apply, in a collaboration of 4 parties including Particle Accelerator Corp (PAC) and NYU/CIMS, for a proposal entitled

"High Power from Fixed-Field Rings for Accelerator-Driven Nuclear Waste Treatment and Energy Production Systems".

The complete text was posted on the ARPA-E site in the late 2014, it can be found in appendix A [1, July 10, 2014 : "Answer to ARPA-E funding opportunity"].

DOE HEP RFI

In April 2014, DOE HEP issued a "Request for Information" regarding a proposed "New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications" :

"The Office of High Energy Physics, as DOE's lead office for long-term accelerator R&D, invites interested parties to provide input on a possible new program to perform R&D leading to advances in particle accelerator technology used in energy and environmental applications." [3]

The RFI received 29 answers, gathered in a dedicated report [1, May 1, 2014 : "Answer to DOE HEP etc."], including (pp. 43-48) C-AD/NSTD contribution, entitled

"A joint response to the DOE request for information regarding 'new R&D programs leading to advances in particle accelerator technology used in energy and environmental applications' by BNL Collider-Accelerator and Nuclear Science and Technology departments"

That document is reproduced in appendix B.

CAS visit at BNL

A visit of a delegation of the Chinese Academy of Sciences took place at BNL on Dec. 3, 2014, organized by BNL Directorate. The agenda of the meeting and ADS-R presentations by the Chinese visitors are available at [1, Dec. 3, 2014].

This was an opportunity to present and discuss the work accomplished by the ADS-R collaboration by that time, as well as possible themes for future collaboration with CAS. A presentation has been given on behalf of the ADS-R think-tank, during that meeting, slides are available at [1, Dec. 11, 2014 : "BNL C-AD/NSTD ADS-R think-tank"].

LDRDs

• A first joint LDRD was submitted, FY15 :

"An hybrid accelerator driven system to burn nuclear waste and deliver carbon neutral energy"

An overview of the main motivations was presented in a preliminary document intended for C-AD and NSTD chairs, reproduced in appendix C.

A set of slides was prepared that detailed the project, FTEs, etc., for presentation and discussions within C-AD and NSTD departments. They are available at [1, May 1, 2014 : " ADS-LDRD_pdf"].

As part of the ADS-R collaboration, discussing and preparing that proposal required a series of meetings, such as found at Feb. 20, 2014 [1, Feb. 20, 2014].

• A second joint LDRD was submitted, FY16 :

"Accelerator driven nuclear waste burner facility"

This C-AD/NSTD collaboration aimed to develop a pre-conceptual design of an accelerator-driven nuclear waste transmutation system with the aim of closing the nuclear fuel cycle, generating clean energy, and integrating a load-following capability. At a high-level, the proposed effort was to identify and to begin to solve accelerator driven system reactor technical, economic, sustainability, safety, reliability, proliferation, and screening issues, with the aim to foster effective R&D at BNL.

The summary of the proposal is available at [1, May 21, 2015 : "FY16 joint LDRD proposal"] :

3.4 Workshops at BNL

Two workshops have been organized at BNL, with active contribution from all parties of the ADS-Reactor collaboration :

• "Transformative Hadron Beamline Facilities", Monday, July 21, 2014 to Wednesday, July 23, 2014, web link
https://indico.bnl.gov/conferenceOtherViews.py?view=nicecompact&confId=719
THB, organized by C-AD, includes an "ADS-R/spallation target R&D" session, Tuesday, July 22, 2014, co-chaired by NSTD and C-AD, with in particular participation of the Director of the European MYRRHA project.

• The 14th International FFAG Workhsop, FFAG'14, Monday, September 22, 2014 to Saturday, September 27, 2014, web link
https://www.bnl.gov/ffag14/
FFAG'14, organized by C-AD, includes a "High power" session (Wednesday, September 24, 2014) chaired by NSTD.

3.5 Collaborations

The ADS-Reactor think-tank framework was an opportunity to launch and energize a series of collaborations, some still on-going :

- INFN/LNS : design studies regarding high power molecular H_2 cyclotron techniques, contact L. Calabretta / INFN/LNS, Catania, Sicily,
- KURRI FFAG Collaboration : high power methods based on scaling FFAG rings, a monthly meeting [4], contacts S. Machida / STFC/RAL and Y. Mori / KURRI,
- Particle Accelerator Corp : high power and CW methods based on non-scaling FFAG lattice methods, an collaboration agreement between PAC and C-AD had been signed earlier, contact C. Johnstone / PAC and Fermilab,
- STFC/RAL, High Intensity Group, CW FFAG R&D, contact S. Sheehy and S. Machida / STFC/RAL,
- NYU/CIMS : space charge simulation developments, high power beam physics, contact A. Cerfon / NYU/CIMS,
- IIAA, University of Huddersfield, contacts R. Cywinski, R. Barlow.

3.6 Student Programs

The ADS-R collaboration framework fosters student activities :

- a PhD program (M. Haj tahar), C-AD / NSTD, in the period Oct. 2013-Oct. 2016 :
" High power ring methods in the accelerator-driven subcritical reactor application"
with Joseph Fourier University, Grenoble, France. The defense will take place later this year. Amongst many written works, a landmark document produced as part of this PhD work is a RAST review [5],
- plans for student exchange, aimed at further high power beam physics/computer simulation developments, with NYU/CIMS.
- possibilities of student exchange with STFC/RAL, Huddersfield.

3.7 Publications

As part of the written contributions resulting from the ADS-R collaboration activities, one finds publications in journals, workshops, conferences including IPAC, NA-PAC, ANS, AccApp, CAARI, in the period 2013-2015.

4 WHAT NEXT ?

These two years of rich and fruitful C-AD - NSTD collaboration have produced a substantial amount of material regarding accelerator driven subcritical reactor science.

A few "master pieces" have been reproduced in appendices A, B, C with in particular appendix C understandable as an overview of the main motivations that led to that collaboration.

The meeting series and the dynamics of the think-tank didactic activities generated knowledge, understanding, critical appreciation of pros and cons regarding a number of aspects of the ADS-R methods in the three sectors : proton-driver, target, reactor. The collaboration in addition took part in BNL Directorate initiatives such as a NPP Strategic Planning Meeting, Chinese CAS visit, FY15 and FY16 LDRDs. A remarkable outcome of these activities and debates is a critical comparison of linacs and fixed field rings, which eventually resulted in the orientation of the FY15 LDRD proposal toward fixed-field ring proton-driver technologies.

The voluminous production of the C-AD / NSTD "ACCELERATOR DRIVEN SUBCRITICAL REACTOR" think-tank collaboration is available at

www.cadops.bnl.gov/AP/ADS_Reactor/

an undoubtedly valuable contribution by experts in the four fields of high power proton accelerators, targetry, reactors, nuclear data, ready for proceeding with these “Accelerator Driven Subcritical Reactor System” think-tank activities at BNL, in the societal field of “energies for the future”.

APPENDIX

The three sections below are essentially excerpts from the ADS-Reactor collaboration web site [1], retained for their reflecting the motivations, and as landmarks, of the think-tank activities.

A Answer to ARPA-E 2013 call

Concept Paper 1002-1878

HIGH POWER FROM FIXED-FIELD RINGS FOR ACCELERATOR-DRIVEN NUCLEAR WASTE TREATMENT AND ENERGY PRODUCTION SYSTEMS

Principal Investigator: François Méot, Brookhaven National Laboratory
Lead Organization: Brookhaven National Laboratory, Upton, NY

1. OVERVIEW

ARPA-E Contact:	
Technical Subcategory	6.6 Nuclear
Funding Request:	$500,000
Project Duration:	12 months
Project Abstract:	This project proposes a detailed scoping of accelerator methods and advances in the area of fixed-field ring accelerator technologies, i.e., cyclotron and Fixed-Field Alternating Gradient (FFAG), towards realizing a transformative accelerator-based solution for a sub-critical nuclear reactor for energy production and nuclear waste burning, with enhanced reliability and cost effectiveness. Studies will include methods for CW acceleration of MW-class proton beams at GeV energies, with enhanced reliability, spallation target power minimization, reduced footprint, and reduced capital and operational costs. A performance matrix will be formulated to compare accelerator technologies, including existing linear accelerator based ones. The project will propose a strategy and roadmap to further the realization of fixed field ring-driven sub-critical reactors, including R&D programs, prototyping and accelerator model stages. The project brings together a team of internationally-recognized accelerator, nuclear reactor and industrial experts.

2. IMPACT

- The current long-term policy for dealing with highly radioactive and long-lived nuclear waste after removal from cooling pools and transition to dry casks is deep geological storage and stewardship for >100,000 years (to reduce the radioactive hazard to that of natural uranium). Even so, the integrity of dry cask storage is only estimated to survive for 60-100 years. Reprocessing plants have not been economically viable and create mixed and high-level waste. Nuclear safety, waste management, environmental and proliferation risk, national security threats, and other challenges remain obstacles to future implementation of nuclear-energy systems. The accelerator-driven sub-critical reactor (ADS-R) technology offers a potential solution to overcome these issues [1], further introduces the concept of green, safe nuclear power with the lowest carbon emission, and is the subject of this proposal.
- Accelerator-based systems have the potential (i) for efficient burning of the most problematic and long-lived minor actinides mitigating both stewardship to ~300 years and reducing legacy proliferation materials, and (ii) for energy production, including from non-fissile fuels such as Thorium. This concept promotes a safe and sustainable nuclear energy future – potentially greener than competing technologies (Fig. 1). In that, this proposal targets two ARPA-E's Mission Areas:

Contains Confidential, Proprietary, or Privileged Information
Exempt from Public Disclosure

1) Enhance the economic and energy security of the United States, and 2) ensure that the United States maintains a lead in developing and deploying advanced energy technologies.

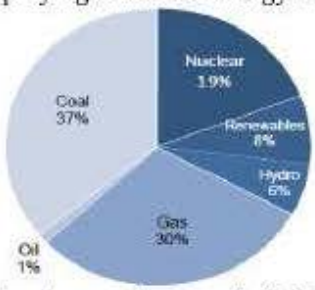

Figure 1: US Electricity production per fuel type [ref. US energy information agency].

3. STATE OF THE ART

- *The* ADS-R *solution being actively pursued* for the transmutation of nuclear waste consists of a high-power linear proton accelerator (Fig. 2-left), a heavy-metal target for the production of spallation neutrons and a sub-critical reactor core neutronically coupled to the target. Europe presently leads in this energy technology with the MYRRHA project in Belgium [2], but China, India, and a number of countries have active, funded programs. *However, competing technologies* to linacs include cyclotrons (Fig. 2-middle) and FFAG accelerators (Fig. 2-right) [3], which are the subject of this proposal.

Figure 2: Left: SNS 1GeV, 1.3MW linac. Middle: PSI 590 MeV, 1.3MW, ~15 m diameter proton cyclotron. Right: 0.2-1 GeV, MW-class compact racetrack CW FFAG design developed for DTRA.

- Linac installations (Fig. 2-left) are large and costly, involving hundreds of meters of magnets and of expensive super-conducting radio-frequency (RF) systems. Their complexity poses not only cost but also reliability challenges. For example the MYRRHA 600 MeV linac is a 400 m long complex whereas the PSI cyclotron (Fig. 2-middle) and injectors which exhibit a similar beam energy and power, use just a few RF systems in a ~30x30 m^2 footprint. With considerably fewer components, fixed-field rings reduce the potential of >1 second trips which can lead to a reactor shut down.

4. INNOVATION

- The concept of a proton, CW fixed-field ring accelerator, capable of delivering multi-MW power at GeV energies with ultra-high reliability, is transformative and innovative. This project proposes a broad scoping study across conventional technology and evaluation of recent innovative, transformational technologies in terms of their near-term viability and application to the objectives outlined in the project plan below. This project requires advanced accelerator design, but also combines innovation in super-conducting components, RF systems and high field magnets. The accelerator R&D

proposed has spin-offs to other challenges identified in the Office of HEP Accelerator R&D Task Force Report: Medicine, Industry, Defense, and Discovery Science [4]. One possible outcome which will be studied is performing nuclear waste treatment at the energy production site eliminating the cost of, and overwhelming public-opposition to transportation of nuclear waste.

- Cyclotrons are isochronous (the revolution time is constant) and thus can operate in CW mode with fixed-frequency RF - so lessening the number of particles per bunch and space charge effects. Proton FFAGs in the low-relativistic regime have traditionally operated using fast cycling swept RF frequencies [3]. On the other hand CW acceleration using fixed RF frequency has been demonstrated in the ultra-relativistic regime at the EMMA prototype FFAG exploiting "serpentine" acceleration, in the UK [5]. Recent advances in FFAGs have demonstrated potential for CW performance in the relativistic ADS-R ring designs, including vertical orbit and other recirculator based implementations - Fig. 2-right. FFAGs additionally feature strong focusing – an advantage over cyclotrons - facilitating higher charge per bunch and smaller beam sizes (important for extraction).
- The innovative concept of CW proton FFAG in low-relativistic regime has not been demonstrated, nor a fixed-field proton ring in the multi-MW, GeV range. Towards this latter end, a working concept will be developed to include required accelerator components and systems, built-in beam reliability, beam delivery and target-core coupling optimization, and accelerator-target interface options.
- Fixed-field ring technologies will be compared to one another and to linacs as part of the project, with metrics that will reflect the technology and advances that can be achieved including: beam energy range and flexibility, beam power, target-core optimal neutron leakage, ranges for current-energy trade-off, beam reliability in terms of trips per unit of time, RF to beam power conversion efficiency, footprint, investment and operation costs.

5. RISKS AND CHALLENGES

- The innovative concept of a CW proton fixed-field ring accelerator is low risk as these new designs employ conventional accelerator dynamics and methods. However, high reliability and power efficiency at MW, GeV levels are challenges, but appear feasible if designed with state-of-the art technologies. The highest risk resides in the progress achievable on target-reactor core coupling to relax the demands on accelerator intensity and target power levels.
- The project will require advances on super-conducting RF and magnet technologies. It will require an innovative R&D program to improve neutron flux optimization [6]. Such trade studies and simultaneous R&D will provide a guide to future investigations, pursuit of promising innovative technologies and eventual prototyping of critical components.
- Technical and economic challenges to overcome include beam reliability, super-conducting RF and magnet technologies, CW fixed-field lattice designs, high power beam acceleration and delivery, beam-target-core coupling optimization, and substantial reductions in investment and operational cost.

6. PROJECT PLAN

- Planned studies will explore design and operational parameters required for beam reliability and technical performance, capital and operation costs all utilizing a unique team of experts from BNL's NSTD and C-AD accelerator physics and engineers, and US university and industrial partners. The studies and R&D proposed will focus on advanced fixed-field ring methods, with the following primary objectives : 1) GeV beam energies and beyond exploiting fixed magnetic fields, 2) CW

operation and strong focusing for delivering multi-MW beam power, 3) power-efficient designs, 4) reliability, 5) beam loss minimization and extraction efficiency, and 6) overall optimization of beam and operational parameters. Different fixed-field ring technologies and concepts will be costed, compared, including ultimately with the linac baseline. Accelerator scoping will include strong focusing, vertical FFAGs, gap stacking, reversed valley field, super-conducting RF and magnet, and extraction septum technologies. Methods for reducing accelerator costs will be investigated. Metrics will be developed that assess the technology readiness, potential, and any significant advances to include: enhanced beam energy range and flexibility, minimized beam losses, optimized target-core coupling, ranges for current-energy trade-off, beam reliability in terms of trips, RF to beam power conversion efficiency, footprint, and capital and operation costs. R&D programs, prototyping and accelerator modeling stages will be proposed.

- An analysis framework will be constructed to fully integrate accelerator and technical system designs (beam optics, space charge, beam losses and activation, RF and magnet design and simulation), with neutronics and particle-matter interaction simulation codes, beam delivery and target-blanket coupling optimization algorithms. A metric and down selection of technologies for future work will be a deliverable in addition to a final report.

7. TEAM

- Organizations that will be involved: Brookhaven National Laboratory: its Collider-Accelerator Department (C-AD) will contribute accelerator R&D, beam delivery and neutronics optimizations; its Nuclear Science and Technology Department (NSTD) will contribute beam parameters, neutronics, reactor physics. The Particle Accelerator Corp (PAC) will contribute expertise and intellectual property in advanced fixed-field CW accelerator design and high-order modeling and simulation. The Courant Institute of Mathematical Sciences (CIMS, NYU) will contribute space charge investigation.
- Key team members: - *From BNL C-AD:* François Méot, accelerator physicist, managed similar projects in Europe, Former director of the European Joint University Accelerator School, Stephen Brooks, Thomas Roser (Department Chair), Diktys Stratakis, Dejan Trbojevic, Nick Tsoupas, Bill Weng, accelerator physicists, Hisham K. Sayed, Research associate, high-power target expert, Malek Haj Tahar, PhD student, specializing in accelerator and target-core physics. *From BNL NSTD:* Nick Brown, Michael Todosow, David Brown, Nick Simos, nuclear reactor physicists, nuclear data, material and high power targetry experts. *From PAC:* Carol Johnstone, accelerator physicist (PAC and Fermilab). *From NYU CIMS:* Antoine Cerfon, Professor, space charge specialist.

REFERENCES

[1] http://science.energy.gov/~/media/hep/pdf/files/pdfs/ADS_White_Paper_final.pdf.
[2] Multi-Purpose Hybrid Research Reactor, http://myrrha.sckcen.be/.
[3] ICFA Beam Dynamics Newsletter 43 - Accelerator Division, Aug. 2007.
[4] OHEP Accelerator R&D Report, May 2012, http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Accelerator_Task_Force_Report.pdf.
[5] EMMA, Nature Physics 8, http://www.nature.com/nphys/journal/v8/n3/full/nphys2179.html.
[6] Spallation Neutron Sources, B. Riemer, High Power Target Workshop, Fermilab, 20-23 May 2014.

B Answer to DOE HEP “Request for Information”

Proposed New Program in Stewardship of Accelerator Technologies for Energy and Environmental Applications.

A joint response to the DOE request for information regarding “new R&D programs leading to advances in particle accelerator technology used in energy and environmental applications” by BNL Collider-Accelerator and Nuclear Science and Technology departments

---

Authors : F. Méot (C-AD), N. Brown, M. Todosow (NSTD)

A classic Accelerator Driven System (ADS) for the transmutation of radioactive waste from spent nuclear fuel (SNF) or for the production of energy consists of a high-power proton accelerator, a heavy metal target for the production of spallation neutrons, and a subcritical blanket where the bulk of the reactions/power production occur. The experience of the joint efforts of the expert teams from the Nuclear Science and Technology and Collider-Accelerator departments in the BNL Accelerator Driven System – Reactor (ADS-R) Working Group suggests that a Stewardship program would have the potential to foster innovation and progress in these applications, i.e., the utilization of high power accelerators coupled to sub-critical blankets for the management of spent fuel from nuclear reactors and energy production. A synergy between multiple skill centers, in an effort to strengthen the relationships and cross-fertilization, would fit in well with the spirit of the proposed Stewardship Program by stressing the need to enable collaboration between experts in the accelerator and reactor communities since ADS systems for waste management or energy production require the expertise of both. Industry and university partnership networks are an essential part of such building such a synergy.

A Stewardship program would ideally be an inter-disciplinary, collaborative framework that would foster the development of novel and cross-disciplinary solutions to the issues associated with the use of ADS for the transmutation of nuclear waste and/or for energy production. This would include identifying, and contributing to solving, technical, economic, sustainability, safety, reliability, proliferation, and screening issues, with the aim to foster effective R&D and to position participants (primarily DOE Labs for the accelerator-related issues as well as for the target and blanket), to be able to identify needed feasibility demonstrations and deployments, and execute the required RD&D. The aim would be to identify and fill the gaps in accelerator transmutation system methods, as related to the management of increasing volumes of high-level waste from power reactors, fission product stockpiles, and minimization of long-lived actinides to improve repository performance. This would foster transformational R&D that is connected to core capabilities, as found in such DOE Laboratory as BNL for example, in Accelerator Science and Technology, Applied Nuclear Science and Technology, Chemical and Molecular Science, and Materials Science.

Application Areas With High Impact

Present technologies deployed to fulfill world's energy needs include fossil fuels (~80%), renewable energies (~15%) and nuclear energy (~5%). Nuclear energy, with 437 reactors in 31 countries, provides 10% of the world's electricity. The largest part is in the USA with 19% of the

electricity from nuclear plants, France has the highest percentage, 80%, whereas 30% of electricity production in EU is from nuclear origin. Nuclear energy has a low carbon footprint, and, compared to fossil energies for instance, very limited waste generation. However, nuclear safety, nuclear waste management, and other environmental and proliferation risks, remain as obstacles to enhanced implementation these energy systems, and the challenges that need to be addressed. The ADS-Reactor technological concept is seen as a path toward a safe and clean-energy future. It has the potential for lowering the cost, increasing the efficiency, and reducing the environmental impact of energy production compared to conventional processes. An ADS-Reactor R&D program has the potential of extended spin-offs of accelerator science, to the other four Grand Challenges identified in the Office of High Energy Physics Accelerator R&D Task Force Report, Medicine, Industry, Defense, Discovery Science.

1. What are the most promising applications of accelerator technology to:

a. Produce safe and clean energy?

- ADS has the benefits of carbon-free production of energy as do critical nuclear reactors
- Coupling of accelerator and subcritical blanket introduces some new challenges
- ADS based "Energy Amplifier" was proposed by Carlo Rubbia and supported for several years by several countries in Europe. Currently being promoted by Aker Solutions in UK

d. Monitor and treat pollutants produced in energy production?

- Proposed in Accelerator Transmutation of Waste (ATW) and Advance Accelerator Applications (AAA) programs under DOE-NE to transmute/burn selected radioactive wastes in reactor spent fuel to reduce its radiotoxicity and improve repository performance
- Several proposed concepts/proponents (e.g., MYRRAH, SMART)

h. Produce alternative fuel sources?

- Can be used to produce fissile material for use in ADS and critical reactors and potentially eliminate the need for enrichment

2. How should Federal, State, or Local regulators consider technologies in determining regulatory compliance?

- No regulations exist for ADS which couples a sub-critical reactor with a high-powered accelerator. The Blanket has most of the same issues as critical reactor (source term, decay heat, containment)

3. What metrics could be used to estimate the long-term impact of investments in new accelerator technologies?

- Similar metrics used in the recently completed Evaluation & Screening of Fuel Cycle Options by DOE-NE would be applicable, including traditional "economics-related" metrics and existence of market incentives/barriers; capital at risk; existing infrastructure.

For Each Proposed Application of Accelerator Technology

Present State of the Technology

Current technologies deployed for the proposed application are primarily based on LWR (PWR essentially) power reactors, and waste management policies such as MOX fuels or storage. Accelerator technology has the potential to revolutionize waste management methods (nowadays essentially relying on storage), based on recycling the spent fuel components including high level

waste, possibly in closed fuel cycles, in complement to other technical solution as fast reactors. ADS systems have specific properties such as, allowing flexibility in fuel composition including use of neutron-poison actinides and other non-fissile fuels, in addition to intrinsic enhanced safety. The US has been, and still is, pioneering in these initiatives as well as in many technological systems involved in ADS-R systems [1,2]. However the US is noticeably absent from the scene in many challenging ADS based waste management R&D programs, such as those currently underway in Europe (the full scale technology demonstrator project MYRRHA), China, India, Japan (first, 150MeV proton driver to core connection, 2009), Russia, South Korea.

4. What are the current technologies deployed for this application?

- Fossil fuelled systems (80%)
- Critical nuclear reactors (5%)

5. Does accelerator technology have the potential to revolutionize the application or make possible something that was previously thought impossible?

- Will offer benefits in burning/transmuting selected radioactive isotopes from spent fuel for waste management purposes.

6. Does the US lead or lag foreign competition in this application area?

- MYRRAH is active, funded project in Europe
- China, India and Japan have various levels of involvement in ADS for production of fissile material and/or transmutation
- Niche studies in US for DOE-NE

7. What are the current obstacles (technical, regulatory, operational, and economic) that prevent the technology from being adopted?

The present state of the technology allows building and operating a demonstrator. The reactor component is comparable to existing installations, and precursors of the required MW class accelerator and spallation target technologies are already in operation in a number of places (PSI, LANSCE, SNS). Accelerator and spallation targetry are *sine-qua-non* components in this application. The accelerator may represent up to 10-15% of the ADS-R investment cost, and require, depending on the technology, up to several tens of MW operation power. As an example, the 85MWth MYRRHA experiment business plan accounts for a 10% efficiency, 15MW operation power, for its 600MeV, 1.5MW super-conducting proton linac [6]. Technical accelerator performance may in some aspects be a limitation in the use of accelerators. For instance, an industrial ADS-Reactor in the GWth range may require up to 30-50MW power beam, depending on reactor technology and the mission of the plant. Accelerator efficiency is thus crucial and justifies superconducting technology R&D programs. Reliability, including stable delivery of the proton beam and footprint on the target is another crucial criterion, with needs beyond those that are currently demonstrated/achievable at existing high power accelerator installations. The accelerator-reactor interface, including beam shaping and delivery, diagnostics, window and spallation target, neutron flux optimization, have been demonstrated at the MW level, however the engineering experience and database for ADS application are very limited, multi-MW beam power scales require furher R&D.

- Issues in all these areas will require R&D efforts

8. How is accelerator technology used in the application?

- High-powered accelerator produces spallation neutrons from a heavy metal target to support/drive a subcritical blanket to produce 100s of megawatts of power and/or transmute isotopes.

9. Does the performance of the accelerator (either technical, operational, or cost) limit the application?

- Cost of accelerator as add-on to subritical blanket which is essentially a reactor
- Wall-plug to beam-power conversion a drain on over-all net power generated
- Reliability comparable to other sources of power production

10. What efforts (both public and private, both domestic and off-shore) currently exist to develop this application?

Existing efforts aimed at developing the ADS process, include the MYRRHA demonstration experiment in Europe, dedicated R&D programs in China, India, Japan, etc. The construction and operation of high power proton accelerators in the US, such as LANSCE, the precursor to SNS, the highest beam power at present, and other Los Alamos LEDA programs, participated in these efforts. These R&D programs, past and on-going, constitute a multi-decade staged approach, from transmutation demonstration (typically, 1GeV, 1-2MW beam power) to industrial scale power generation (1-2GeV beam, tens of MW), with an increasing progression towards technological complexity.

11. What are the perceived and actual market barriers for the final product?

Societal and market barriers for the final product are those common to conventional nuclear power reactors. As to the former, they are matters of safety, carbon footprint, non-proliferation. As to the latter, difficulties are in the complexity, the expertise required for operation, maintenance, which the accelerator component could increase further relative to a purely reactor-based implementation depending on technological choices. Technical barriers are a matter of accelerator electrical power efficiency (wall plug-to-beam power), beam reliability and redundancy/fault-recovery issues, development of magnet and RF superconducting technologies, hands-on maintenance criteria, beam-reactor interfacing issues as high power beam delivery, spallation target and its coupling to the reactor core, etc.

12. What aspects of the overall technology solution are proprietary or likely to be developed as proprietary, and what aspects are non-proprietary?

Defining the Stewardship Need

13. What is the present technology readiness level (TRL) of the accelerator technology for this application?

The present state of the technology allows building and operating a demonstrator. However, the readiness level of the accelerator technology for this application varies depending on the mission and on the accelerator type. Technical readiness for the various accelerator concepts and components, and for their integration, needs be established through a dedicated development program, covering accelerator technology, target technology, beam dynamics simulations, redundancy methods, reliability. Defining the roadmap of such a development program, is an effort that could readily be started in a DOE Laboratory as BNL, in the frame of a multiple-directorate collaboration.

14. What resources (both skill and infrastructure) are needed to advance the technology to a prototype phase?

Cross-disciplinary solutions to the issues associated with accelerator driven transmutation of nuclear waste and energy production are necessary to best carry out the required R&D. Typical resources to warrant success of an R&D program are, core capabilities in Accelerator Science and Technology, Applied Nuclear Science and Technology, Chemical and Molecular Science, Materials, Condensed Matter Science. An R&D program would be best managed by a cross-disciplinary steering group, comprised of experts from, at least, Accelerator and Reactor directorates, and including partnership with national nuclear industry companies, small business, Universities, and, including partnering between DOE laboratories, in the – very successful - model of the SNS project.

- Accelerator and reactor expertise in design, manufacture and operation

17. Would partnering with a DOE National Laboratory be beneficial for the required R&D? Which laboratories could provide the greatest leverage?

- Partnering with DOE National Lab is essential because that is where the expertise with the needed accelerator technology lies (BNL, FERMI, ORNL, J-Lab, LANL)

REFERENCES

[1] Office of HEP Accelerator R&D task force, May 2012.
[2] A Roadmap For Developing ATW Technology, A report to Congress, Oct. 1999.
[3] Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production, H. Aït Abderrahimh et al., Sept. 17, 2010.
[4] A European Roadmap for the Development of ADS Technology for Nuclear Waste Transmutation, The European Technical Working Group on ADS, April 2001.
[5] Accelerator Driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles, OECD-NEA, 2002.
[6] A. Abderrahim, ThEC13 Conference, CERN, Oct. 28-31, 2013.

C FY15 LDRD, goals : A summary for NSTD and C-AD Department Chairs

The document below, concerning FY15 LDRD calls, was written by the ADS-R think-tank, intended to NSTD and C-AD Chairs, in preparation to the submission of a joint C-AD/NSTD proposal regarding an ADS-R design study. It was aimed at establishing being a frame for future joint C-AD/NSTD LDRD proposals at BNL.

FUTURE OF ENERGY
Joint C-AD/NSTD initiative for a LDRD thrust area in FY15

The "Accelerator-Driven Subcritical Reactor" study group at BNL was launched in the spring of 2013 as a joint "think-tank" involving accelerator and nuclear technology experts from the C-AD and NSTD departments, and has since been holding bi-weekly meetings, documented at www.cadops.bnl.gov/AP/ADS_Reactor/. The ADSR group enthusiastically encourages a joint proposal (or joint proposals) with inter-directorate collaboration regarding the accelerator-driven transmutation of actinides and fission products. We suggest that a key focus area for the upcoming LDRD call for proposals should be the development of breakthrough science advances related to the accelerator-driven transmutation, including nuclear waste incineration and other applications. The goal of the focus area in the upcoming LDRD call would be to develop novel and cross-disciplinary solutions to the problem of accelerator driven transmutation of nuclear waste (ATW), with scope in both basic science and applied research. We aim to stimulate transformational R&D that is connected to the BNL core capabilities in Accelerator Science and Technology, Applied Nuclear Science and Technology, Chemical and Molecular Science, Condensed Matter Physics and Materials Science, and potentially in other BNL departments. This includes identifying and beginning to solve technical, economic, sustainability, safety, reliability, proliferation, and screening issues, with the aim to foster effective R&D and to position BNL to be able to participate in feasibility demonstrations and deployments, when they eventually occur. We aim to identify and fill the gaps in accelerator transmutation system methods, as related to the management of increasing volumes of high-level waste from power reactors, fission product stockpiles, minimization of long-lived actinides, and other potential accelerator transmutation applications like medical isotope production. These objectives will foster collaboration within BNL as well as with other laboratories, universities (such as Stony Brook), and industry. Some primary goals in studying accelerator driven transmutation are to:

- develop deployment pathways for sustainable, CO2-free energy production
- explore transformational solutions to challenging energy and waste problems for the future
- expand on-going BNL programs related to evaluation and screening of potential sustainable fuel cycles
- identify potential supporting high power accelerator, neutron source, and fuel cycle R&D directions
- position BNL in on-going domestic and international R&D collaborations
- attract young scientists to cutting-edge programs in the future of energy, and retain them.

Facilities

BNL has a variety of hadron beam acceleration and delivery facilities at flexible energies and intensities (BLIP, NSRL, Booster, AGS, Tandem), which are of potential use in performing ADSR R&D studies. Supported by distributed computing resources, these facilities allow theoretical and experimental exploration, benchmarking, and prototyping, in addressing three sets of issues:

1. the integrated system and accelerator-reactor interface, such as
    a. window, plasma and other window-less concepts,
    b. targetry,
    c. safety,
d. computer tool development (simulation,modeling,etc.),
2. multi-MW class accelerator driver, including
    a. comparative studies between ring methods, ring and linac methods,
    b. high power beam delivery system,
    c. accelerator-reactor interfacing,
3. reactor technology, such as
    a. core configuration and fuel form (solid vs. liquid),
    b. target-blanket interface and design,
    c. ionic liquid carriers,
    d. beam-core interaction.

Existing BNL facilities and resources would be instrumental in ensuring the success of an LDRD program.

Expertise

Brookhaven National Laboratory is renowned for pre-eminent expertise in accelerator and nuclear reactor systems. Over the past 60 years, BNL has contributed solutions to many challenging problems related to spallation, targetry, nuclear data, materials in extreme environments, and nuclear reactor systems. The present ADSR study group collaboration between C-AD and NSTD concentrates on identifying unique growth opportunities for inter-directorate cooperation between the Nuclear and Particle Physics directorate and the Global and Regional Solutions Directorate. Participation from other directorates is also logical and possible. Potential joint LDRD activities would enhance BNL expertise, and could establish BNL as a national leader in cross-disciplinary basic science research on the Future of Energy.

Synergies

An ADSR LDRD thrust area would have synergies with the eRHIC program (for example, in the matter of FFAG lattice design studies), as well as with many other on-going C-AD and NSTD activities, and potential for synergies with several other directorates. Components of a joint LDRD could be directed specifically towards the following domains:

- high power, energy efficient accelerators,
- collimation and window,
- high power spallation targetry,
- accelerator-reactor interface,
- complex carrier liquids for target nuclides,
- reactor core configuration studies,
- nuclear fuel cycle,
- reactor physics,
- nuclear data,
- materials in extreme environments for advanced energy systems.

Proposed LDRD thrust area: Future of Energy

The proposed LDRD thrust area would be to identify and to begin to solve ADSR technical, economic, sustainability, safety, reliability, proliferation, screening issues, with the aim to foster effective R&D and to position BNL to be able to participate in feasibility demonstrations and deployments, when they eventually occur. In particular:

- guide basic science R&D to significantly reduce long-term storage requirements for high level waste,
- develop innovative and transformational potential programs in the accelerator transmutation of waste,
- identify (and study) relevant issues, such as target-and-blanket and accelerator design,
- identify the needs for additional nuclear and material data and basic science experiments,
- increase the scope and efficiency of inter-directorate collaboration.

References

[1] www.cadops.bnl.gov/AP/ADS_Reactor/index.html

[2] https://arpa-e-foa.energy.gov/

[3] The “Request for Information on Energy and Environmental Applications of Accelerators” file, April 2014, at http://science.energy.gov/hep/community-resources/reports/

[4] International Collaboration on KURRI FFAGs and Other Similar Machines http://hadron.kek.jp/FFAG/colabo/

[5] AcceleratorReactor Coupling for Energy Production in Advanced Nuclear Fuel Cycles, F. Heidet, N.R. Brown, M. Haj Tahar, Reviews of Accelerator Science and Technology, Vol. 8 (2015) 116.
Cyclotrons and FFAG Accelerators as Drivers for ADS, L. Calabretta, F. Méot, Reviews of Accelerator Science and Technology, Vol. 8 (2015) 77-97.

[6] Private communication, Associate Laboratory Director for Nuclear & Particle Physics, December 2014.